STRUCTURAL, METAMORPHIC AND PETROCHEMICAL ASPECTS OF NAPPE DISPLACEMENT IN THE CENTRAL SCANDES

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ABSTRACT

This paper summarizes and comments upon previous studies on structural and metamorphic features related to extensive nappe displacement, carried out by the author (and co-authors) in a critical section (Jämtland -Trøndelag) of the Scandinavian Caledonides (Scandes). Studies on the magma-tectonic significance of two prominent groups of allochthonous volcanites are also reviewed.

The tectonostratigraphic work leading to the recognition of very extensive nappe displacement is reviewed. The large-scale pinch-and-swell tectonics of the displacement, manifest by mega-lenses, is described. Extreme attenuation, but also the persistence of discrete nappes characterize the composite mega-lens. Basal thrusts are zones of intense stretching, which do not cut across stratigraphic sections but meet in the necks of the lens.

A scheme for the structural evolution of the northern Trondheim region is presented. The benefit of detailed microstructural and microchemical analyses as a method to elucidate the tectonometamorphic evolution of nappe terrains is emphasized. However, the ambiguity of inferred "regional" foliations when occurring in the far-travelled allochthon is pointed out.

P-T conditions at the top of the basement of the Tømmerås Window (western Trøndelag) are estimated to $P \geq 0.7$ GPa and $T < 550^{o}C$. With regard to the weak deformation, low temperatures and incomplete metamorphic equilibration in the western windows, current concepts about western Trøndelag as the structural and metamorphic core of the Scandes may require modification. It is argued that the very prominent system of late to post-Caledonian high-angle faults, which dissects western Norway (Vestranden), may control the distribution of high- and low-grade metamorphic rocks in that area.

Current models describing the perturbation of the conductive geotherm by horizontal movements in the crust are tentatively applied to the central Scandes. Available biostratigraphic and radiometric brackets for the Late Silurian to Early Devonian evolution of the Trondheim region indicate that uplift followed very soon upon nappe displacement and that erosion rates were as high as 0.25 cm/year. It is concluded that transient blueschist facies conditions may well have prevailed at the base of the nappe pile after its emplacement onto the Baltoscandian margin.

Evidences for strain-induced prograde metamorphism in the nappe terrain of the Scandes are presented.

The occurrence (Tømmerås) of an alkaline subgroup of the Ottfjäll Dolerites corroborates the previous interpretation of these transitional (oceanic/non-oceanic) dolerites as being related to crustal tension and the opening of the Iapetus Ocean. The homogeneity and consistent variation pattern of element concentrations in the low-grade, massive Seve amphibolites (Mt. Sylarna) are taken to indicate immobility of the elements (P,Ti,Zr,Y,Nb) which are critical for the magmatectonic classification and interpretation of these amphibolites as spilitized basalts of the sea floor of the early Iapetus Ocean. Very rare alkaline-ultrabasic dykes occurring in three different nappes along the inner Trondheimsfjorden are considered late to post-Caledonian in age.

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Introduction

This paper summarizes and comments upon seven articles published during the period 1978-1980, to report investigations carried out mainly in the northern Trondheim region of the central Scandinavian Caledonides (central Scandes):

1. Andreasson, P.G. 1978: Aspects on the lithology and structure of the Leksdalsvann Group, central Norwegian Caledonides. *Norsk Geologisk Tidsskrift 58, 109-112.*

2. Andreasson, P.G., Gee, D.G. and Kumpulainen, R. 1979: Some remarks on the Steinkjer Mega-boudin. *Norsk Geologisk Tidsskrift 58, 305-307.*

3. Andreasson, P.G., Solyom, Z. and Roberts, D. 1979: Petrochemistry and tectonic significance of alkaline and alkaline-ultrabasic dykes in the Leksdal Nappe, northern Trondheim region, Norway. *Norges Geologiske Undersøkelse 348, 47-71.*

4. Andreasson, P.G. 1980: Metamorphism in the Tømmeråsarea, western Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 101 (for 1979), 273-290.*

5. Solyom, Z., Andreasson, P.G. and Johansson, Ingrid 1979: Geochemistry of amphibolites from Mt. Sylarna, central Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 101, 17-25.*

6. Andreasson, P.G. and Lagerblad, B. 1980: Occurrences and significance of inverted metamorphic gradients in the western Scandinavian Caledonides. *Journal of the Geological Society of London 137, 1-12.*

7. Andreasson, P.G. and Gorbatschev, R. 1980: Metamorphism in extensive nappe terrains: a study of the central Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 102, 335-357.*

Reference is also made to a paper which is now in press:

8. Andreasson, P.G. and Johansson, L. 1982: The Snåsa Mega-lens, west-central Norwegian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 104.*

All above reports are the result of research within the *Caledonide Research Project (CRP;* Sweden's contribution to the International Geodynamics Project) and the Swedish contribution to the *Caledonide Orogen Project (CO)* of the International Geological Correlation Programme. Both projects were supported by the Swedish Natural Sciences Research Council.

Following a brief introductory note on the central Scandes, the contents of the listed papers are treated under various headlines, which reflect some major topics of CRP and CO research in this part of the orogen. The main theme of my summary is the tectonometamorphic implication of extensive nappe displacement.

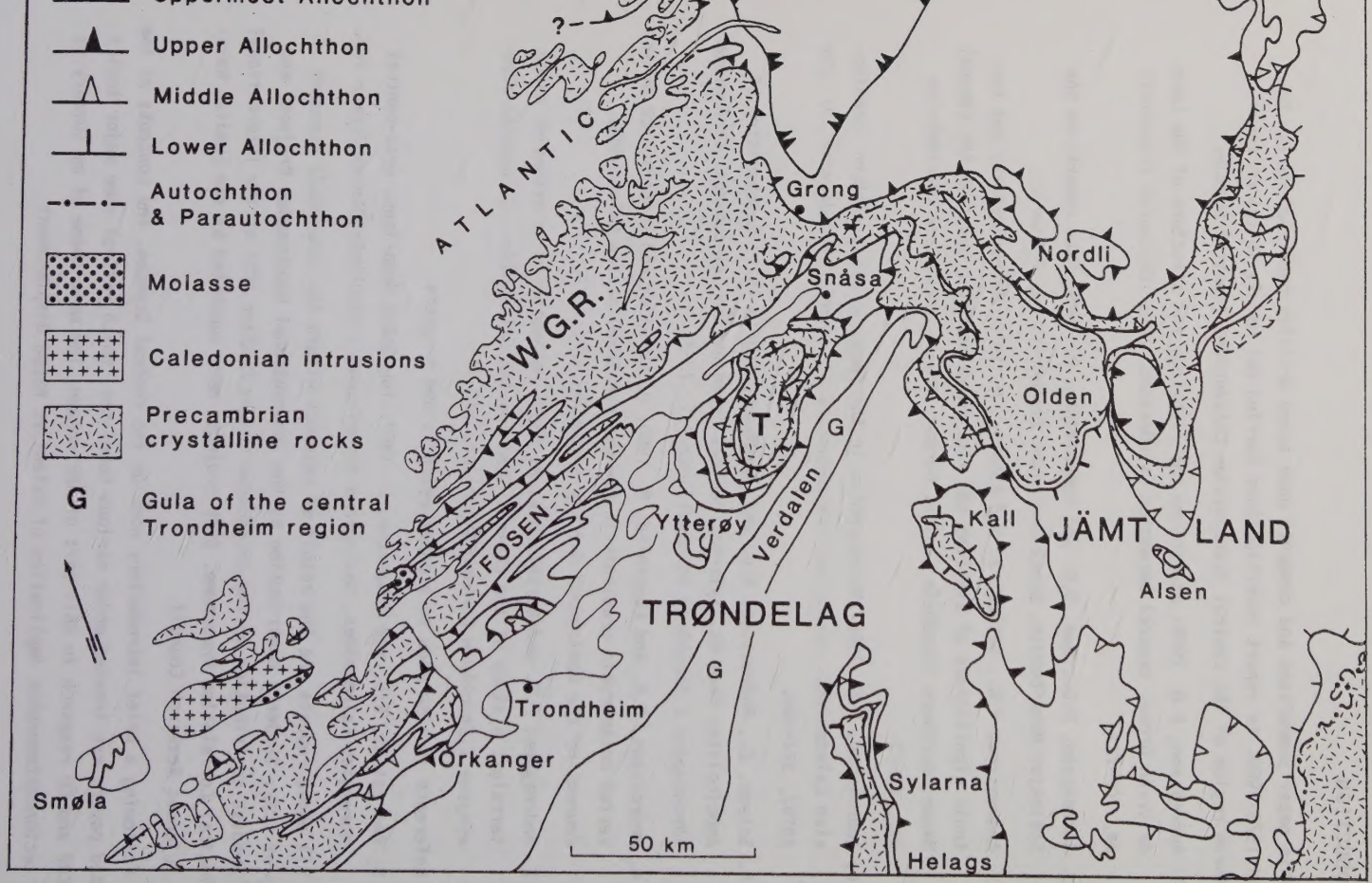


FIG.1. Place-name map of the Jämtland-Trøndelag region. The tectonostratigraphy is simplified from Gee et al. (in press). W.G.R. = Western Gneiss Region (Vestranden). T = Tømmerås Window (Antiform).

The central Scandes

Several circumstances contribute to make the central Scandes an ideal ground for the study of structural and metamorphic features related to nappe displacement (4: p.278, 7: p. 353). The total distance of displacement was very large. Displacement involved large-scale pinch-and-swell tectonics producing a mega-lens geometry which allows the inspection of nearly complete tectonostratigraphic sections in a number of windows. This facilitates safe correlation. Biostratigraphical age bracketing of the displacement is possible. As different from the situation in most other segments of the orogen, post-thrusting heating by intrusions or reactivated basement was absent or subordinate everywhere except in the westernmost Scandes. In combination with rapid uplift and therefore incomplete recovery of the geotherm, this prevented recrystallization and obliteration of microstructural and microchemical information on the tectonometamorphic evolution. The deep level of erosion allows the physical conditions to be evaluated at great tectonic depths. In the central Scandes, transverse culminations of basement (the Grong-Olden Culmination, Fig. 1) and deeply eroded cross lineaments provide almost continuous exposure from the nappe front in the east to the Atlantic 200 km farther west. Increasing basement involvement and tectonometamorphism of both basement and cover towards the interior of the orogen are other major subjects conveniently studied in the central Scandes.

When nappe theory was introduced and debated in Scandinavia a century ago (Törnebohm 1872, 1888, 1896; Svenonius 1881; Högbom 1894; Brøgger 1893) and when the estimates of displacement distances later increased (Högbom 1909; Asklund 1938), the arguments were derived mainly from investigations in the Jämtland-Trøndelag region. Having been for a long time in the focus of stratigraphic and structural interest (cf. Gee 1975a and Roberts 1978), this section was selected for the geotraverse of the CRP (p. 1) in 1973. As a result of intense Swedish and Norwegian CRP and IGCP activities the following years saw a rapid accumulation of information and the introduction of new ideas. Up-to-date reviews of our present state of knowledge of this section of the Scandes can be found in papers on basement-cover relations (Gee 1980), stratigraphy (Zachrisson 1969; Gee and Zachrisson 1974; Roberts 1975; Hardenby 1980, J. Bergström 1980 a.o.), tectonostratigraphy (Gee and Kumpulainen 1980; Gee and Wolff 1981 a.o.), metamorphism (7; Guezou 1978) and volcanism Stephens 1980; Furnes et al. 1979).

This summary follows the IGCP Tectonostratigraphic Map (Gee et al. in press) for the subdivision and nomenclature of nappe successions. Since there is growing evidence of an early Caledonian episode of diastrophism in Scandinavia, the name *Scandian* is employed here for the late orogenic episode, i.e. the one which "may have commenced as early as the Lower Silurian, and probably continued into the Devonian" (Gee 1975a: p. 496), and the physiographic expression of which are the *Scandes* (Gee 1975a; Ljungner 1948).

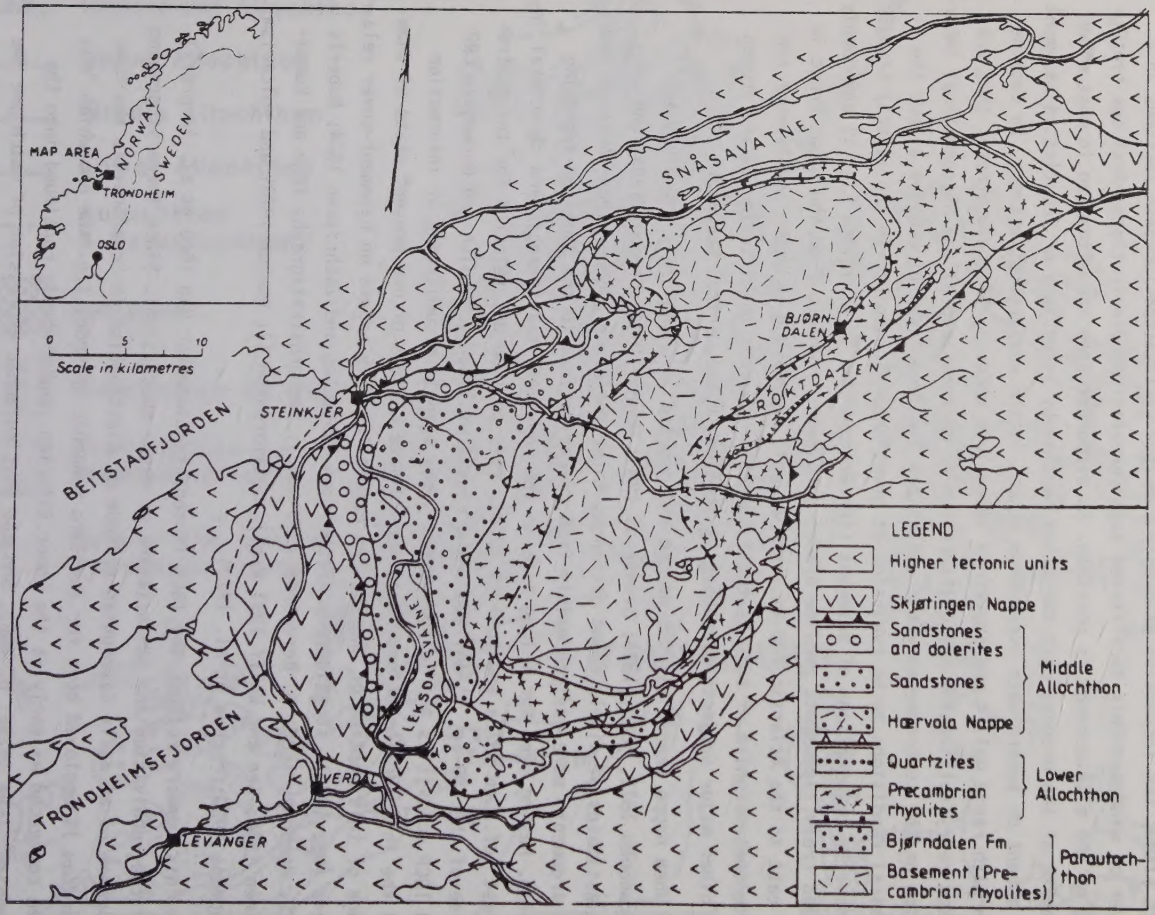


FIG. 2. Tectonostratigraphy of the Tømmerås Antiform. From Gee & Wolff (1981) with slight modification.

THE CONCEPT OF VERY EXTENSIVE NAPPE DISPLACEMENT

The approximately 150 km long Grong-Olden Culmination exposes pre-Caledonian crystalline basement (Fig. 1). Foslie (1958, 1959, 1960) recognized the principal structure of the culmination. He traced the Lower Palaeozoic cover of the foreland and Jämtland autochthon-parautochthon (Jämtland Supergroup; Gee 1975b) westwards along the northern and southern margins of the culmination. The cover sediments overlie a basement core composed of Precambrian porphyry-granite lithologies with subordinate metabasites. The sediments are overridden by a nappe comprising essentially the same lithologies as the core. Oftedahl (1956) interpreted this discontinuity as the basal thrust of the "Great Seve Nappe" of Asklund (1938). In that sense, the thrust requires that the cover be allochthonous as far west as the Norwegian coast. However, Oftedahl (1964) was also intrigued by the concordance between basement and cover in the westernmost districts and preferred to regard the cover as rooted "from Ottadalen in the south to the Grong culmination in the north" (Oftedahl 1964: p. 10). Peacey (1964) published a map of the Tømmerås Window which was to become a contribution of great value. She mapped a concentric veneer (Fig. 2: Bjørndalen Formation) of sediments (quartzite, phyllite, black phyllite, and limestone) which she interpreted as Precambrian (Bjørntjern schist). Although Peacey (1964: Fig. 4) discussed the possibility of thrusting along the margin of the window, she preferred to regard the cover as rooted, which opinion persisted until the early seventies (Roberts et al. 1970).

Based on stratigraphic considerations of the allochthonous cover in the eastern part of the orogen, Gee and Zachrisson (1974) inferred an allochthonous nature of "all Trøndelag successions". Zachrisson (1973) suggested allochthoneity on the basis of the wedging out (p. 10) of the units, particularly the Seve. Decisive evidence was provided Gee´s (1974) correlation of the Bjørntjern schist of the Tømmerås Window with the Jämtland Supergroup of the Grong-Olden Culmination. In Jämtland, the Särv Nappes with their rootless dolerite dykes (Strömberg 1961) provide the classical evidence of nappe translation. The recognition of Särv type sediments and rootless dolerite dykes in the Tømmerås Antiform (Gee 1977) was therefore a major advance. In a recent review of tectonostratigraphic research in the Trondheim region Roberts and Wolff (1981) write: "Acceptance of a southeastward displacement of some of the thrust sheets by up to several hundred kilometres from their pre-orogenic locations (Gale and Roberts 1974, Gee 1975, 1978) permits the assessment of the palaeogeography...". The authors omit the contributions of Zachrisson 1973 and Gee 1974 and 1977, thereby misleading the reader about the development of the concept of very extensive nappe displacement. It must be pointed out, that this concept did not emerge from the results of trace element studies in the *uppermost* unit of the cover sequence, i.e. the Støren Nappe (Gale & Roberts 1974), but from pain-

staking mapping by Foslie and Peacey and the recognition of the full implications of their mapping by subsequent authors. It was the identification of the *lowermost* allochthonous unit and the extension of the principal eastern nappes into Trøndela that required that the entire cover succession was derived, nappe by nappe, from successively more distant westerly locations.

My own work involved tracing of tectonic and metamorphic breaks, if any, betwe the lithological units of the Tømmerås Antiform. Guided by the map of Peacey (196 I found a thrust zone separating the Leksdalsvann Group of meta-arkosic sediments from the porphyry-granite rocks of the window margin (Andreasson 1976). The previ ly inferred primary variations in the Leksdalsvann Group could be shown to be the result of recrystallization due to strains increasing towards the basal thrust of the group. Peacey (1964) had interpreted the concentric pattern defined by "micaceous leptite", "granite gneiss" and the Bjørntjern schist as a primary Precambri stratigraphic succession resulting from pre-Caledonian deposition around a baseme dome (cf. also Oftedahl 1964). Referring to the similarity between twinned alkali feldspars found in the basement and the "leptite", she interpreted the latter as sediment derived by weathering of its substratum. "Granite gneiss" with recrystal zed K-feldspars was considered to be a metamorphosed "micaceous leptite". However the "micaceous leptite" and the "granite gneiss" are products of strain-related r crystallization of the Precambrian rhyolite porphyry in the thrust zones. Most ig neous feldspars have been broken down to a.o. white mica, while some K-feldspars form in blastomylonitic varieties. The concentric pattern is the result of late-Caledonian folding (F 3, p. 12) and crossfolding (F 4).

In 1977, Gee extended the principal nappes of the Jämtland allochthon into th Tømmerås area. The nappes thus correlated comprise the Offerdal (Lower Leksdalsva Group of Peacey 1964), the Särv (lowermost part of the Lower Snåsa Group and the upper part of the Leksdalsvann Group), and the Seve (Lower Snåsa Group). This cor lation required a further increase of inferred displacement distances. On the bas of variuos direct and indirect evidence, Gee (1977) concluded that "the Seve Comp has been displaced at least 150 km over the Särv Nappes, the Särv Nappes at least 200 km over the Offerdal Nappe, and the Offerdal Nappe at least 150 km over the underlying tectonic units".

Subsequent work refined (1,2) and confirmed (3,5,6) the allochthonous interpr tation of the Tømmerås Antiform. Six traverses across the basal Leksdalsvann Grou (1) demonstrated identical transformations of the feldspathic sandstones into gar netiferous mica schists and phyllonitic mica schists in the vicinity of the basal thrust. Such development of the Offerdal sediments is characteristic also of the type area (Andreasson & Lindqvist 1981) and the eastern periphery of the Grong-Olden Culmination (Andreasson & Johansson 1981: Stop 3-5). Strongly tectonized,

concordant metabasites occur in the basal thrust of the Offerdal Nappe (1,3). At least some of them can be shown to belong to the tectonized margin of the window (i.e. the dykes at Hofstad, 3). However, the augen-gneissic Haervola Granite (Wolff 1960, 1976) of the southeastern margin of the Tømmeråsen Window is also cut by metabasite dykes (Andreasson, unpublished results). This dyke-intruded augen-gneissic unit possibly corresponds to similar lithologies in the Orkanger area (the Risberget Nappe of Krill, in Gee & Wolff 1981), occurring in approximately the same tectonostratigraphic position. In one of the studies (3), the name Leksdal Nappe has been used for the nappe containing the Leksdalsvann Group and the underlying porphyry-granite nappe. This was done in order to comply as much as possible with the official map published by Norges Geologiske Undersøkelse (D. Roberts, written communication). In my opinion, this name is inappropriate. Since the Särv Nappe is included in the Leksdal Nappe, the latter comprises also units of the Lower Snåsa Group. Originally defined (Wolff 1976) without the acceptance of a thrust at the base of the Leksdalsvann Group, the term Leksdal Nappe covers three major nappes of the central Scandes (Seve, Särv, Offerdal) and an imbricated sheet of basement. If nappes with so different derivation should at all be grouped in a single term, one should at least refer to the sequence as "the Leksdal Nappe Complex". In a recent review, Roberts and Wolff (1981) subdivide the Leksdal Nappe into the Leksdalsvatn Nappe and the Haervola Nappe. The former is in turn subdivided into two nappes correlated with the Särv and Offerdal Nappes. The term Haervola Nappe is used for the "subjacent augen gneisses and blastomylonites". In Roberts and Wolff's map, this nappe corresponds to the imbricate basement sheet (the porphyry-granite nappe). They correlate the Haervola Nappe with the "Tännäs Nappe in Sweden". However, the Tännäs Augen Gneiss Nappe (Röshoff 1978) has a decidedly different lithology, a different degree of deformation and a different derivation. Moreover, it belongs to the Middle Allochthon. In the Tømmeråsen Window, augen-gneissic rocks are subordinate and restricted to nappe margins. As a rock, the Haervola Granite may possibly be correlated with the Tännäs Augen Gneiss. However, it can also correspond to the Olden Granite (Klingspor & Troëng 1980; Troëng 1981) and if so, belong to the porphyry-granite nappe. The granite is, nevertheless, very subordinate in comparison to the well preserved porphyries and the fine- to medium-grained granite of the imbricate sheet. This sheet also contains veneers of quartzite and subordinate phyllite belonging to the Jämtland Supergroup. As a result of the sweeping revision suggested by Roberts and Wolff (1981), these horizons of the Jämtland Supergroup now appear to belong to the Middle Allochthon (Fig. 2). In addition, their revision suppresses an important evidence of increasing basement shortening westwards (Gee 1980).

In order to emphasize the affinity to the underlying basement, the porphyry-granite nappe has in one paper been referred to as the "basement nappe" (6). In view of the inherent contradiction this usage should be abandoned.

The petrochemical specifics of the dolerite dykes in the uppermost Leksdalsvann Group include a somewhat paradoxical (p. 10) tholeiitic affinity as well as the existence of an alkaline subgroup. This is in excellent agreement with the large reference population of analyzed Ottfjäll Dolerites (Solyom et al. 1979; for simplicity, the dolerites of the Särv Nappes are referred to as "Särv dolerites" in the following text) and emphasizes the transitional magma character of both groups of dykes. The overall similarity between the uppermost Leksdalsvann Group (including the basal part of the Lower Snåsa Group) and the Särv rocks also accounts for some petrographical properties of the dykes (3) and sedimentological features of their host rock (R. Kumpulainen, pers. comm.). Subsequent field work (Andreasson & Johansson 1981; 8) has demonstrated the occurrence of Särv-type metasediments infolded into the Vestranden gneisses, which suggests that we may not yet have identified the westernmost occurrence of the Särv Nappes.

Metamorphic breaks and inversions have been identified (5,6) between various units of the Tømmerås cover sequence, which confirms its allochthonous character. Porphyroblasts concentrated to the contacts between these units serve as indicators of tectonization (5,6,7,8). P-T gradients across tectonic contacts have sometimes been flattened by metamorphic convergence, i.e. by retrogression at the base of the overthrusted ("hotter") nappe and prograde recrystallization at the top of the overridden unit (6,7; Armstrong & Dick 1974). This process is likely to be particularly efficient if the overridden units are rich in water. However, metamorphic breaks may be defined also in terms of *fabric contrasts*. In some cases, such contrasts may be identified already in the field. An example is the striking contrast between the well preserved feldspathic sandstones of the uppermost Leksdalsvann Group and the well recrystallized amphibolites, schists and gneisses of the overlying Lower Snåsa Group (Gee 1974; 5,6: Fig. 4). In other cases, careful microstructural and microchemical analysis may be required. Much of my work on the tectonometamorphism in the Tømmerås area was devoted to such detailed studies (1,5,6). Fabric contrasts are likely to be important criteria of allochthonous basement-cover relationships farther west (Bryhni & Brastad 1980; 8).

As it was recognized that an important element of stretching had been involved in nappe displacement, it became obvious that pure translation could have accounted for only half of the total displacement of at least 1 000 km (Gee 1978). The next chapter comments on this remarkable tectonic feature of the Scandian allochthon.

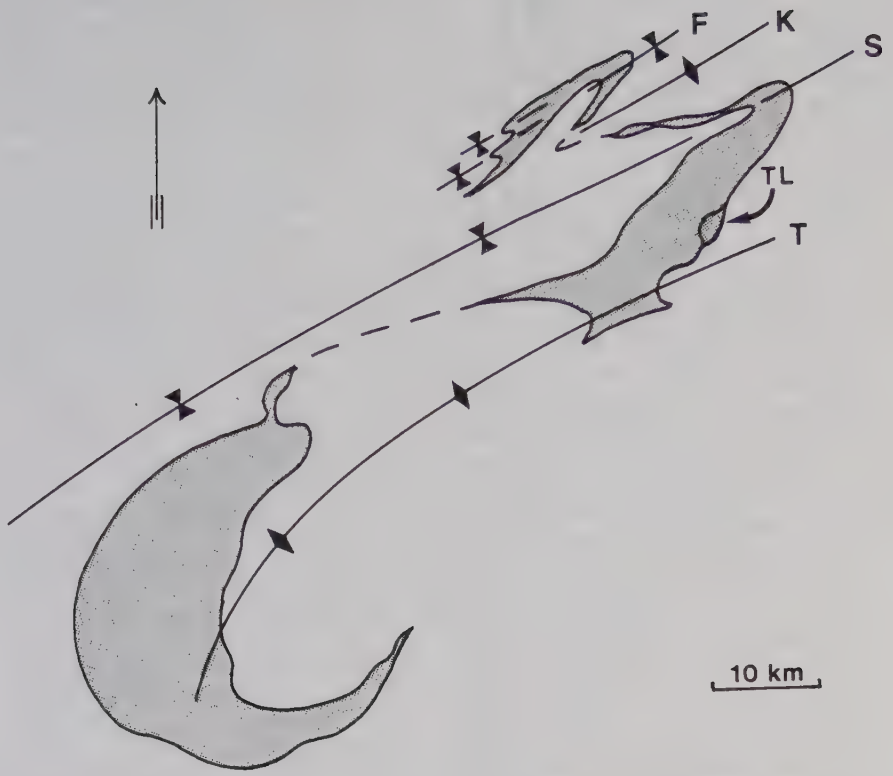


FIG. 3. Out-crop patterns of the Steinkjer and Snåsa Mega-lenses, as defined by the Offerdal, Särv, Seve and Gula Nappes. Regional (F 3) folds: F = Flåtjern Synform; K = Kolåsfjell Antiform; S = Snåsa Synform; T = Tømmerås Antiform. TL = Turtbakktjørna Lens (Kautsky 1978). Note the persistence of the attenuated nappe sequence in the tight Flåtjern and Kolåsfjell folds.

Boudinage is a characteristic mesostructure in the far-travelled allochthon. Here we consider only the large-scale feature, which is referred to as a mega-lens. The concept of *composite mega-lenses* (Gee 1976, 1977, 1978; Häggbom 1976, 1980) partly emerged from the recognition of a conspicuous wedging-out of nappes towards the west (Zachrisson 1969, 1973; Nicholson and Rutland 1969). The "very large-scale lens (Gee 1977) occurring southwest of the Tømmerås Window (Fig. 3) is at least 2 k thick and comprises units of the Offerdal, Särv and Seve Nappes. This composite mega-lens (the Steinkjer Mega-boudin); 2) pinches out against the basement of the Tømmerås Window, only to swell again farther north in the Snåsa Mega-lens (8), whic is made up of units of the Offerdal, Särv, Seve, Gula and Støren Nappes. The Turt-bakktjørna Lens (Kautsky 1978) composed of Offerdal and Särv units forms a distinct swell in the eastern margin of the Snåsa Mega-lens (Fig. 3: "TL"). Häggbom (1980) described the Krutfjellet Nappe of the Nordland-Västerbotten Köli as "several gigan tic, laterally semiconnected, quasilenticular parts". From the same area, I. Ramber (1981) described the approximately 1 km thick Brakfjellet Lens. Like the Turtbakk-tjørna Lens, this lens is clearly recognized in aerial photographs.

Extreme attenuation, but also the persistence of discrete nappes characterize the composite mega-lenses (8). In the Snåsa Synform, the thickness of the Gula Napp is reduced dramatically from at least 1 km in the eastern limb of the synform to less than 50 m in the western limb. As a rule, only the most competent units (ores, cherts, amphibolites) survived such thinning. The attenuated Gula Nappe can be traced westwards through a tightly folded antiform-synform pair. South of Nordli (Fig. 3), 3 km of road cuttings expose the entire cover sequence above the Lower Allochthon (i.e. from bottom to top: augen gneiss nappe, Offerdal, Särv, Seve and Köli Nappes). Here, the Offerdal and Särv Nappes have been thinned to thicknesses below 30 m. The road passes up and down through the cover sequence, which has been pinched out completely leaving the uppermost unit (Köli) to rest directly on Pre-cambrian crystalline rocks of the Lower Allochthon (Andreasson & Johansson 1981: Stop 3-5).

On a theoretical and experimental basis, H. Ramberg (1966, 1967, 1980, 1981) advocated nappe displacement by gravitational collapse. He stated (1980: p. 265) that gravity-propelled horizontal movement of nappes "is only possible if the rocks are weak enough to sag and spread under their own weight". Mega-lenses are often remarkably heterogeneous with regard to internal deformation. Whereas some lower units (e.g. the Särv) are not penetratively deformed and had largely been displaced by translation on external thrusts, the upper units (e.g. the Köli or the Støren) of the same lens were as a rule thoroughly penetrated and flattened (8). This may, of course, reflect temperature differences between the nappes of different deriva-

tion. I. Ramberg (1981) saw a relationship between the variations of competency between various lithologies of the Köli Nappes and the abundance of tectonic lenses in these nappes. The S-shaped arrangement of the internal lithologies of the Turtbakktjørna and Brakfjellet Lenses suggests that these kilometre-thick lenses were rotated within their phyllonitic envelopes.

Cooper (1980) inferred that nappe displacement in the western Scandes was achieved by gravity gliding rather than gravitational collapse and spreading. He stated that basal thrusts cut down-section at the trailing edges of the nappes, which is a geometry incompatible with spreading, and that there is a "lack of lateral stratigraphic continuity between successive nappes". As to his first statement, our study of the Snåsa Mega-Lens has shown that the basal thrusts cut neither up- nor down-section at the trailing edges. Basal thrusts are zones of intense stretching, which meet in the necks of lenses, which is due to the concomitant thinning of the nappes. They have not been seen to intersect each other. Some nappes thin more than others, but this appears to be due to competency differences and is not related to their stratigraphic level. Concerning Cooper´s second statement, the apparent lack of lateral continuity is, no doubt, partly due to the lack of systematic mapping and previous failure to recognize, for instance, deformed and metamorphosed Särv Nappe equivalents in the western districts.

Evidence provided by the composite mega-lenses accordingly supports, but also places important evolutionary constraints on models involving nappe displacement by gravitational collapse and spreading. The weight of evidence indicates that collapse acted upon a pre-existing pile of nappes (Gee 1978). How and when this pile was aggregated remains to be assessed. Plate tectonic theory suggests that we should envisage a process of underplating of the Baltoscandian margin and its sedimentary cover which resulted in a pile of "imbricate sheets". As this pile grew by stacking from the base, the upper nappes gradually became gravitationally unstable and collapsed. Construction and collapse could thus have been synchronous. While this model is admittedly hypothetical it could perhaps explain the radiometric evidence of early (485 ± 50 Ma; Rb-Sr whole rock isochron, Claesson 1980) thrusting of Precambrian crystalline rocks (the Tännäs Augen Gneiss Nappe).

The idea of Scandian nappe displacement by internal and therefore pervasive deformation is attractive because it allows the interpretation of the pervasive foliation of the allochthon as a product, essentially, of Scandian nappe displacement. This, in turn, greatly facilitates regional correlation of structures and metamorphic events. However, as will be discussed in the next chapter, such an interpretation of the regional foliation in the central Scandes would be an oversimplification.

Timing of the extensive nappe displacement in the central Scandes

As has been mentioned in the previous chapter, the lower nappes have not always been penetratively deformed during their displacement. These nappes were derived from more peripheral and therefore relatively cold parts of the orogen. In contrast the high-grade nappes of the Upper and Uppermost Allochthons stem from the orogenic interior and are generally believed to have been "hot" during their translation. It is difficult to understand how such a "hot" and therefore presumably ductile allochthon could have resisted penetrative deformation during displacement. Inferences from radiometric (Klingspor & Gee 1981), microstructural and microchemical results (Andreasson 1981) obtained from the Gula Nappe nevertheless suggest that early "regional" foliations survived the Scandian penetrative deformation. Some geologists report even Precambrian foliations in the Seve Nappes (Reymer et al. 1980).

Failure to assess the relative age and regional significance of various foliations in the Trondheim Nappe Complex has led to much confusion about the structural evolution of the northern Trondheim region. This could at least partly have been avoided if investigations had not been confined to the upper allochthonous complex but had included correlation with deeper tectonic levels. Results obtained from the Tømmerås area (Andreasson 1978; 5,6) are at variance with the interpretation of the structural history of the region presented in many publications (Roberts 1967; Wolff 1967; Roberts et al. 1970; Wolff 1976, 1979; Roberts 1978; Wolff & Roberts 1980). Differences of opinion pertain in particular to the age of the "regional" foliation, the age of the Tømmerås-Verdal antiform-synform pair, and the concept of a "central mushroom-antiform" (Roberts 1978) in the Trondheim region. The Tømmerås model is, on the other hand, partly compatible with results obtained by Olesen et al. (1973) and Guezou (1977, 1978) in the central Trondheim region and by Roberts (1979) and Lutro (1979) in the Grong district adjacent in the north. In a recent review, Roberts and Wolff (1981) accepted the results of other students of the region and revised their model accordingly. Although the "mushroom model" is inconsistent with an allochthonous nature of the Tømmerås cover sequence (Gee 1974) it, nevertheless, survived several revisions (Roberts 1978; Wolff & Roberts 1980). A review of different models has recently been given by Hardenby and Lagerblad (in press).

Structural evidence. The NE-SW trending Tømmerås Antiform folded the mega-lenses and the associated thrusts with their characteristic, E-W trending, "transverse" linear structures (4,6). Whereas this *F 3 folding* was gentle in the Tømmerås area, it locally raised the regional foliations to steep attitudes in the adjacent Snåsa and Verdal synforms. In the "mushroom" model (cf. above), these steep dips of late origin were considered to be early dips. Parasitic mesofolds related to the Tømmerås Antiform include kink folds and crenulations with flat-lying axial surfaces, which dip to the east in the western limb of the antiform but have westerly dip in its

eastern limb. Roberts (1978: p. 35) incorrectly interpreted these late folds as being related to the main phase of gravitational collapse involving boudinage and stretching. In the Tømmerås area, the folds crenulate the phyllonitic and "transverse" lineation related to nappe displacement. The designation of these folds as F 4 (6) is abandoned here because of their close genetic relationship with F 3 folding. In the Snåsa area and the adjacent part of Vestranden, the F 3 folding of the mega-lenses was tight (8; Andreasson & Johansson 1981). *F 4 folding* resulted in gentle (NW-SE) crossfolding (8).

Detailed study of the structural evolution of the basement-cover sequence in the Tømmerås area (1,4,6) demonstrated a complex structural development during the Scandian nappe displacement. Structures occurring in the vicinity of thrusts underwent a characteristic development with increasing strain. They include early isoclinal mesofolds with approximately N-S axial trends. Necks of boudinaged quartz veins have similar trends. The unambiguous concentration of these structures to Scandian (base of Offerdal Nappe and the thrust above the Jämtland Supergroup a.o.) thrusts and their gradual change with increasing strain preclude their affinity to any pre-Scandian phase of folding. These folds have been designated *early F 2 folds* (4: p. 276). Megafolds of F 2 age are not easily recognized in the strongly attenuated and pinched nappe sequence.

On the cleavage planes of strongly flattened early mesofolds, a conspicuous crenulation formed at right angles to the fold axes. The development of this lineation appears to have been dependent on irregularities defined by minute garnet knots. Where quartz veins have been folded, straight fibres of quartz grew perpendicular to the axis of the host folds (8: Fig. 7). With increasing strain also the fold axes became affected by stretching. Early folds with mildly curvilinear axes (8: Fig. 7) developed into strongly non-cylindrical folds or sheath folds. Such folds abound in phyllonites where quartz segregations occur in the deepest thrusts, which possibly reflects the role of "mechanical contrasts and irregularities" (Cobbold & Quinquis 1980) during their formation. "Transverse" linear structures have been recognized at tectonic contacts in the Western Gneiss Region west of Snåsa (Andreasson & Johansson 1981). The partly or completely reorientated folds and the "transverse" lineations described above have been designated as *late F 2 folds* (4,8).

Indirect evidence of *pre- or early Scandian* tectonometamorphic events is provided by fabric contrasts (cf. p. 8) between, for instance, the Lower Snåsa Group and the uppermost Leksdalsvann Group. The Lower Snåsa Group (except its lowermost part) must have been affected by at least one event prior to its juxtaposition with the Leksdalsvann unit (Gee 1974). I have designated this phase as *D 1*, but it is understood that there can have existed several pre-Scandian orogenic episodes (4: p. 276). In the Snåsa Mega-lens, the Gula Nappe preserves folds and fabrics which predate the pervasive Scandian foliation (8: Fig. 6). In this particular case,

identification of the pervasive foliation as Scandian was possible owing to the pinching-out of the Middle Allochthon and the emplacement of the Gula Nappe closely above the basal thrust. In Jämtland, this basal thrust overrides Silurian strata. In the Snåsa area, it is possible to trace the pervasive foliation of the thrust into the Gula Nappe, where it can be shown to wrap around domains with relict fabrics. However, with regard to the complex development of Scandian structures, these relict folds and fabrics need not necessarily be entirely pre-Scandian. They may merely represent early F 2 folding. On the other hand, the high-grade metamorphism indicated by relict fabrics (Andreasson 1981) requires a location of the energy source somewhere in the west (cf. p. 28).

In thicker successions of the Upper Allochthon at a distance from the basal thrusts, the age of folds and fabrics are not easily assessed without some kind of dating. In central Verdalen, for instance, some of the steeply plunging but E-W trending folds may belong to the Scandian group of "transverse" folds rather than to a pre-Scandian episode of folding. In fact, their variable axial trends (Roberts & Wolff 1981) suggest that they belong to the more or less rotated F 2 folds described above. However, the occurrence of Ordovician folds and foliations in the Verdalen Gula (Fig. 1) has been demonstrated by radiometric datings of trondhjemite dykes (p. 12).

Roberts and Wolff (1981) introduced the name "Finnmarkian" for "F 1 folds" in the upper allochthonous complex of the Trondheim region. They do not provide any description (or references to published descriptions) of these folds but mention that they are "early" and "generally isoclinal". However, "early" folds in the far-travelled allochthon may represent an event which occurred at the Laurentian margin (Gee 1982). Apart from such ambiguity of the term "Finnmarkian" when used outside Finnmark, our present state of knowledge on the structural evolution of the Trondheim region does not allow correlation based on so loose definitions.

A recent model for the tectonic evolution of the Trondheim region (Furnes et al. 1979) postulates juxtaposition of the Gula and Støren Nappes already in pre-Middle Arenig. So far, we have found little evidence to support such an early juxtaposition of the nappes (8). In the Snåsa Mega-lens, the present-day contact between the nappe was established during the Scandian nappe displacement and the structures occurring in this contact are exclusively related to the late D 2 pervasive deformation. Whereas the internal structure of the Gula Nappe is complex and was accompanied by polyphase metamorphism, the rocks of the Støren Nappe are comparatively well preserved and of low metamorphic grade. It is difficult to understand how this contrast between the two nappes could have survived polyphase Silurian tectonometamorphism.

Råheim et al. (1979) recorded Svecofennian ages in the Precambrian crystalline rocks ("basement gneisses") subjacent to the garnet-mica schists of the Namsen Formation in the Grong area. Referring to the "absence of a major structural and meta-

morphic break between the basement gneisses and the garnet-mica schist unit" they interpreted the (mylonitic) structures in the contact zone and in the garnet-mica schist as being Precambrian in age. This classical argument had earlier been used by Oftedahl (1964) when he, in the same area, erroneously interpreted the concordance of structures at the same contact as "primary layering" (op. cit. p. 6). Johansson (8 and in prep.) rejected the interpretation of Råheim and coworkers on the basis of a.o. the fact that the contact in question separates the Namsen Formation lithologies (Seve Nappe) from underlying, Late Precambrian Särv psammites and metadolerites. This occurs in the Lurudal river section 10 km south of the locality sampled by Råheim and coworkers. Moreover, the "basement" gneisses do not belong to the basement but to a nappe of Precambrian crystalline rocks which is thrust above Jämtland Supergroup sediments (Johansson 1981).

Geochronological evidence. Since my own work was not concerned with these particular aspects, the reader is referred to review articles listed on page 3. With regard to the age of the Scandian nappe displacement, it is important that successions of Late Llandovery age occur in the Upper Allochthon (Fig.7). In Jämtland, the Rödeberget sandstones are the youngest Palaeozoic rocks overridden by nappes. They are "considered to be no younger than Mid-Silurian in age" (L.Karis in Gee & Kumpulainen 1980). Less extensive thrusting, which has not been considered here, continued into the Devonian. Wilson (1981) concluded that regional metamorphism, folding and "major nappe emplacement" occurred after $405^{+}_{-}9$ Ma (a Rb-Sr whole-rock isochron age). However, as mentioned above (p.11), Rb-Sr isochron ages obtained from mylonites in the Middle Allochthon suggest that movements on deeper thrusts could have started as early as 485 Ma (Claesson 1980).

Vogt (1929, 1945) was the first to demonstrate an episodic orogenic evolution in the Trondheim region. He identified Ordovician "disturbances" manifested by extensive conglomerates. This early view has been contested by Roberts (1971) but is supported by the recent recognition of drastic crustal changes (ophiolite obduction) in Late Cambrian to Early Ordovician and also a period of relative stability during the ensuing deposition of a volcano-sedimentary succession upon the ophiolite (Furnes et al. 1979; Bruton & Bockelie 1980; Ryan et al. 1980). As already mentioned (p. 12), radiometric results indicate regional tectonometamorphism of Gula rocks in the Early to Middle-Ordovician.

THE COMBINATION OF DETAILED STRUCTURAL AND PETROLOGICAL ANALYSES AS A METHOD TO ELUCIDATE THE TECTONOMETAMORPHIC EVOLUTION OF NAPPE TERRAINS

The previous chapter outlined the polyphase structural history of the allochthon, emphasizing that there exist several foliations and fabrics with "regionally metamorphic" implication. In some cases, the foliation may be defined by only single mineral phases, in other cases by complete equilibrium assemblages. In the ideal case, the foliations should permit the assessment of P-T conditions prevailing at various stages of the tectonic evolution of a region.

Methods of geothermometry and -barometry require equilibrium, which has often been taken for granted or has been assumed on more or less valid grounds. However, when microprobes came into extensive use, it became evident that equilibrium could be restricted to microdomains such as the margins of a crystal. While petrologists were soon able to adjust their analytical routines to such imperfections of Nature, the great informative value of disequilibrium features such as zonations of crystals relict phases and arrested reactions was accepted only recently (cf. Tracy & Robinson 1980; Thompson 1981). To the best of my knowledge, my study of metamorphism in the Tømmerås area (4) was one of the first attempts to bracket the various deformational phases of a region in terms of P and T. However, most of my laboratory work for paper (4) was done in 1977, at a time when microprobe facilities were meagre in Sweden and the number of analyses had to be kept low. Therefore, the chemical data presented for some mineral groups may be statistically not very representative. However, the importance of study (4) is less in the accuracy of the P-T data than in its methodological approach. When reckoning also with the evidence obtained from paragenetical analysis, the recognition of inter- syn- and postkinematic P-T conditions can hardly be disputed.

Subsequent pilot work in the Gula Nappe indicated an exceedingly complex tectonometamorphic evolution involving drastic changes of the P/T ratio. Additional microstructural and -chemical data are required before a coherent P-T evolution of this nappe can be established and modelled in regional geological contexts.

With regard to the often incomplete recrystallization and metamorphic homogeneization of the allochthon (p. 13), combined microstructural and -chemical analyses are likely to become widely used in future reconstructions of the tectonometamorphic history of the Scandes. However, a cautionary general comment appears justified: as mentioned above, the correlation between a microfabric, and the regional deformational episode is seldom straightforward, indeed it may often prove impossible without close cooperation with an isotope geologist. The interpretation of the order of growth of porphyroblasts is still based on "common sense" criteria, which invite a

subjective treatment of often ambiguous relationships. The very common situation where a porphyroblast of, say, garnet carries abundant small inclusions of, for instance, staurolite, does not necessarily imply that the garnet postdates the staurolite. As pointed out by Vernon (1977), the two phases may have grown simultaneously but the staurolite grew from many small nuclei, whereas the garnet grew from a few. Microprobe traverses across contacts between phases may be needed to assess trends of reactions. Despite all papers written about garnet zonation, this feature is still far from being fully understood. A recent study by Sivaprakash (1981) may serve as an example. It demonstrated that the decrease in Fe and the concomitant increase in Mn and Ca towards the rims of garnet crystals were not due to retrogression, which is the standard interpretation. Instead, the rims of the garnets lost their Fe to staurolite in a *prograde* reaction, in which the antipathetic elements Mn and Ca were also adjusted.

Microstructures must never be treated as phenomena isolated from meso- and megastructures. Microchemical properties of minerals must never be interpreted without consideration of the paragenetic context. These seemingly trivial aspects deserve increased attention.

P-T CONDITIONS AT THE DEEPEST TECTONOSTRATIGRAPHIC LEVELS OF THE CENTRAL SCANDES

The estimates of Caledonian P-T conditions in the Tømmerås-Snåsa area are based on mineral parageneses, inferred reactions, and the partitioning of Fe^{2+} and Mg between garnet and biotite (4,6; Andreasson 1981 and in prep.). With regard to the parageneses, it is important to note, that chlorite, phengite, green biotite, albite and sphene are not retrogressive in character but were involved in prograde growth. Green biotite is rimmed by brown biotite, phengite is replaced by less phengitic muscovite, and chlorite is cut across by muscovite flakes. Albite and plagioclase have stable grain-boundary relationships. We do not deny that there exist zones of retrogression within the thrusts of the Tømmerås area. However, careful inspection of the continuous change of structures and parageneses in the vicinity of such retrograde zones clearly demonstrates that they are related to late, minor thrusting or adjustment of the nappes. There is also retrogressive chloritization of postkinematic garnets. This is a typical feature elsewhere in the eastern Scandes, and was probably related to uplift.

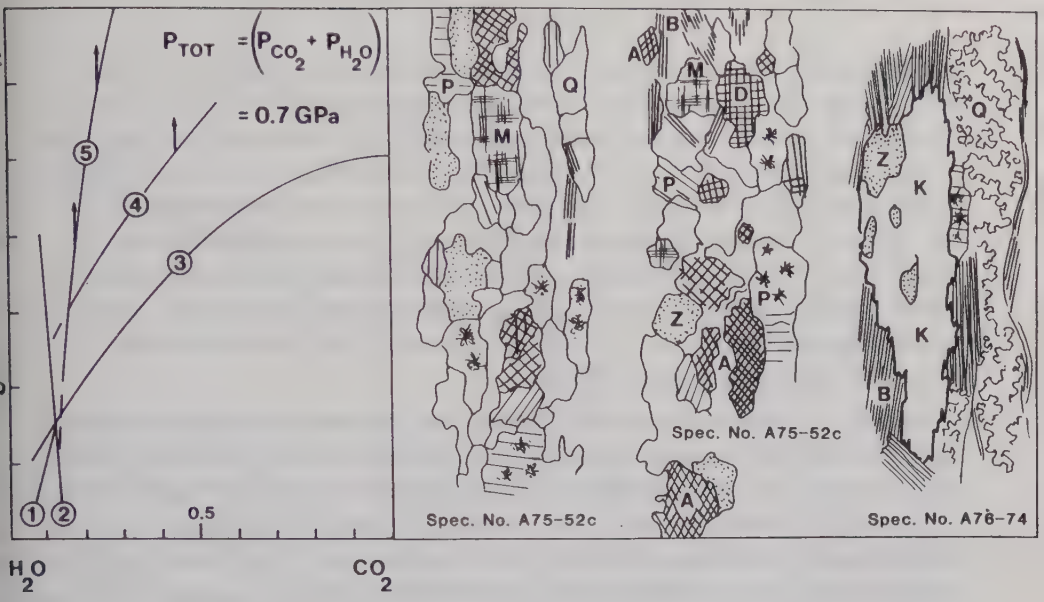
Kyanite overgrown by almandine occurs in one exposure of strongly tectonized Jämtland Supergroup sediments in the western limb of the Tømmerås Antiform (Varg-

haugan, 6; Andreasson & Johansson 1981). The extreme but very local enrichment of kyanite in this locality, and the associated segregations of quartz and albite were interpreted (6) as the result of stress-induced diffusional mass transfer of Si and alkalis leading to the enrichment of Al. Such strong local enrichment of kyanite has been observed in several thrusts of the Snåsa area (Johansson & Andreasson in prep.) and is not assigned regional metamorphic significance (cf., however, p. 22). The same applies to the very rare staurolite found in a sample from Varghaugan.

Ten K_D values for garnet-biotite pairs obtained from sub-Särv units of the Tømmerås area indicate peak temperatures of 550°C (4,6). This estimate was made assuming all Fe in the biotites to be Fe^{2+}. If Fe^{3+} is present, the estimated temperature is lower. Depth estimates for the window are less precise. The use of Velde´s (1965, 1967; Saliot & Velde 1982) geobarometer based on the Si^{4+} content of phengite is controversial, but the 0.4 GPa value obtained for the Tømmerås Window is certainly a conservative estimate (4: Fig. 8). Maximum pressures of 0.8 GPa were inferred from the upper stability of the assemblage quartz + margarite + zoisite (6: Fig. 5). The best pressure estimate is probably provided by the obviously stable coexistence of aligned kyanite and zoisite in the thrusting-related foliation of the basal Gula Nappe (Andreasson 1981 and Fig. 4). It suggests 0.7-0.8 GPa as a minimum pressure for the deeper thrusts (Chatterjee 1976).

The unique but useful paragenesis plagioclase (An 40) + zoisite + diopside + amphibole + microcline + muscovite was found in a sample from the basal Gula Nappe in the Snåsa Mega-lens (Andreasson 1981). The assemblage defines the pervasive foliation of inferred Scandian age (p. 14). Zoisite is particularly abundant along narrow more penetratively deformed zones in the thin section. Tremolite appears to be a retrograde product of diopside. The textural relationships thus suggest that the assemblage in Fig. 4 formed during penetrative deformation and hydration of a calc-silicate rock of originally higher metamorphic grade. The assemblage provides three isobaric invariant points indicating temperatures around 550°C for a total pressure of 0.7 GPa.

In the Offerdal Nappe, peak temperatures were estimated from synkinematic assemblages and garnet-biotite pairs (4). In the basal thrust, syn- to postkinematic porphyroblasts were used for the same purpose. In this case, "synkinematic" means mineral growth during the development of the Scandian thrusting-related foliation. Such growth can be observed close to the lower and upper margins of the nappe. Postkinematic porphyroblasts postdate the thrusting-related foliation and fabric. This remarkable character of metamorphism in northwestern Trøndelag is the subject of the two following chapters.



1: 3 muscovite + 4 calcite + 6 quartz = 2 zoisite + 3 microcline + 4 CO_2 + 2 H_2O.
2: 3 anorthite + calcite + H_2O = 2 zoisite + CO_2.
3: muscovite + calcite + 2 quartz = microcline + anorthite + CO_2 + H_2O.
4: 5 phlogopite + 6 calcite + 24 quartz = 3 tremolite + 5 microcline + 2 H_2O + 6 CO_2.
5: tremolite + 3 calcite + 2 quartz = 5 diopside + 3 CO_2 + H_2O.

A = amphibole B = biotite D = diopside K = kyanite M = microcline P = plagioclase (often corroded: stars) Q = quartz Z = zoisite.

FIG. 4. T-X(H_2O-CO_2) diagram for equilibria inferred from mineral assemblages in calc-pelites of the Gula Nappe (Andreasson 1981), as seen under the microscope. The pervasive foliation is the thrusting-related (Late D 2) foliation, cf. p. 18. Muscovite and calcite are subordinate in the areas of the thin section shown in the figure.

The curves for the CaO-$KAlO_2$-MgO-Al_2O_3-SiO_2-CO_2-H_2O system refer to iron-free phases. Arrows indicate the predicted displacement of the curves with increasing FeO (Thompson 1975). The invariant point at the intersection of (2) and (3) was approximately drawn in for 0.7 GPa and an An-content of the plagioclase of 40 mol.-% (Hewitt 1973). T. Widmark kindly recalculated reactions (2) and (3) for the same conditions. Using data from Helgeson et al. (1978) he preliminary obtained an intersection at c. 540°C and X_{CO_2} c. 0.02. The intersection of (4) and (5) was extrapolated (90°C higher) from the invariant point at 0.4 GPa of LeAnderson (1981).

The occurrence of prograde strain-induced metamorphism in the Scandes

Most reports on metamorphism in shear zones describe retrogressive processes. Prograde, strain-related metamorphism has been studied theoretically and experimentally, but very few studies consider geological field evidence. The lower nappes of the eastern Scandes provide the preconditions for such evidence to be preserved (Andreasson & Lindqvist 1981), since there was almost no metamorphism of the thrust mass and overridden units prior to thrusting and no post-emplacement heating by intrusions or reactivated basement. Uplift and cooling were rapid. Considering our present meagre knowledge of the processes causing the observed features, the concept "strain-induced" is used here in a very wide sense. It includes features of diverse energetic, kinetic and chemical origins.

My paper on metamorphism in the Tømmerås area (4) demonstrated the existence of microstructural and microchemical evidence of prograde growth of mica and garnet with increasing strain at the margins of the Offerdal Nappe. Interkinematic garnet, i.e. garnet in the well preserved inner parts of the nappe, is sparse, rich in Mn and Ca (Fig. 5) and not in equilibrium with associated green biotite and phengite. Synkinematic garnet is almandine coexisting with brown biotite. In marly beds, hornblende develops comcomitantly with the growth of synkinematic garnet. Synkinematic minerals are confined to a narrow zone close to the nappe margin (cf. p. 18). Postkinematic garnet occurs in the thrust zone. It is richer in Ca and Mn than the synkinematic garnet (Fig. 5). With increasing strain, the Offerdal sediments underwent substantial chemical reconstitution (4: Table 1). Such changes of bulk composition can influence the amounts of minerals but also their first entry with increasing grade. An increase in Al due to loss of Si would, for instance, stabilize phengite and delay the income of biotite (Mather 1970; Vernon 1976; 4: Fig. 6). In the Offerdal Nappe, brown biotite formed despite a bulk increase in Al suggesting a distinct increase in metamorphic grade.

In the basal thrust and the overridden sediments of the Jämtland Supergroup, a very irregular pattern of recrystallization resulted from strongly varying intensities of strain (6: p. 227). The Jämtland Supergroup is locally 200 m thick but may pinch out completely. We inferred a relationship between increasing strain, influx of water and the buffering capacity of graphite in black phyllite. Other features related to the varying intensity of tectonization along the basal thrust include differential transfer of elements in the Varghaugan phyllonites (cf. p. 18). We also demonstrated (7: Fig. 3 and p. 350) postkinematic garnet growth in all major thrust zones of the Tømmerås area. Garnets develop in quartz "sweat-outs" of the phyllonites in the basal Offerdal Nappe. We discussed variuos possible mechanisms behind such postkinematic growth, suggesting that precrystallization strain could have triggered diffusion and nucleation but could also have been "stored in the thrust for a considerable time, eventually providing the excess energy needed to transgress kinetic

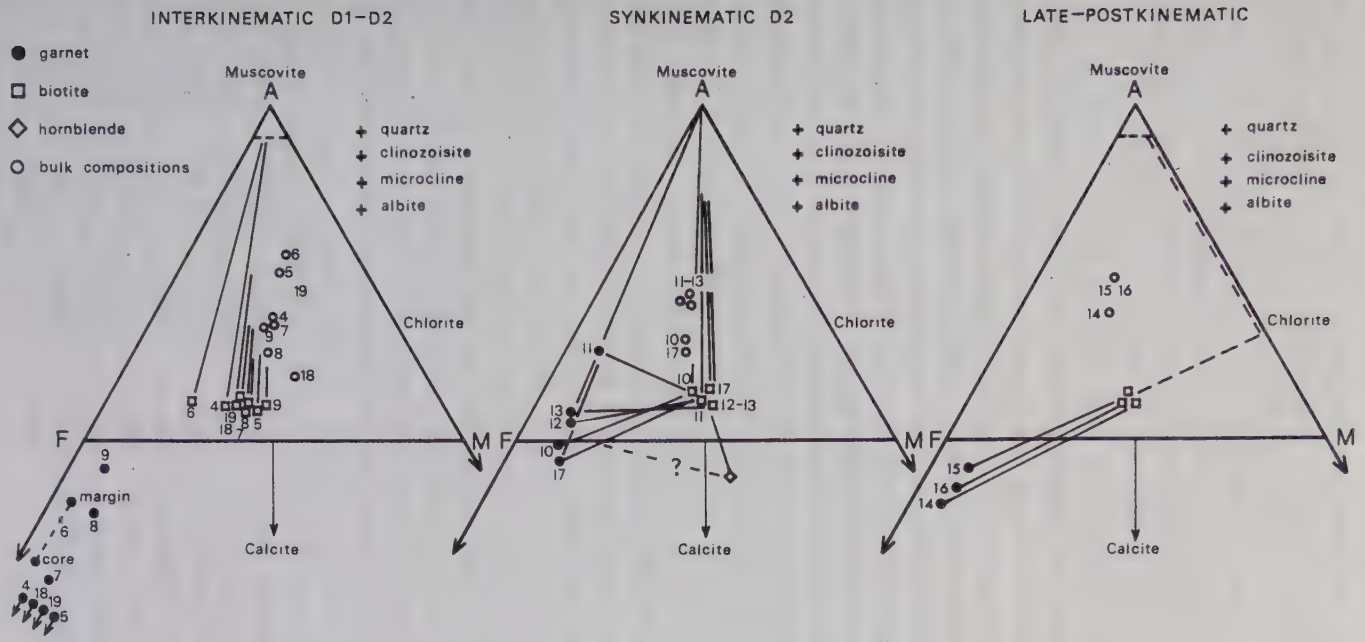


FIG. 5. AFMC diagram (Griffin & Styles 1976) describing the variation of mineral chemistry during progressive recrystallization of the Offerdal meta-arkoses with increasing strain (Tømmeråsen Antiform). "Interkinematic" garnets occur in the well preserved parts of the core of the nappe; "synkinematic" garnets in the thrusting-related foliation of the margins of the nappe. "Postkinematic" garnets cut this foliation. ● = Garnet. □ = Biotite. ◇ = Hornblende. ○ = Bulk compositions. Cf. 4: Tables 1-7 and Fig. 5 for details about the analyses and the AFMC diagram.

barriers of metamorphic reactions. As the thermal gradient rose after thrusting and strain was released, the metamorphic reactions took place in the thrust zone only, even though the other conditions of metamorphism (P,T,X) could have been similar throughout the considered area". Subsequent work (8) demonstrated postkinematic growth of garnet confined to shear zones across metadolerites of the Särv Nappe. These idioblastic garnets are disticntly zoned, having dark red cores and light red rims. I have observed such postkinematic garnet growth in northern Jämtland (Ströms Vattudal), Västerbotten (Borgahällan) and Norrbotten (Silvervägen) in places where dolerites have been deformed in the upper thrust of the Särv Nappe.

Although the direct or indirect contribution of strain to the prograde recrystallization of Offerdal sediments in the Tømmerås area can hardly be disputed, that area may be a less good choice for the study of such metamorphism. This is due to its proximity to the Western Gneiss Region, which is by some writers considered to be the metamorphic "core" of the Scandes (see next chapter). Investigations of strain-related metamorphism were therefore made in the Alsen area (Fig. 1), where there cannot have been any disturbance by high regional temperatures. The Alsen Klippe is situated only 50 km from the Caledonian Front. This is the type area of the Offerdal Nappe, where it overrides sediments which according to recent geothermometric studies of illite crystallinity (Kisch 1980) and conodont coloration (S.Bergström 1980) attained maximum temperatures of c. 350°C. In the vicinity of the basal thrust of the Offerdal Nappe, there is late growth of biotite and garnet. The latter mineral formed concomitantly with the development of a characteristic crenulation (Andreasson & Lindqvist in prep.). Some of the garnets have idioblastic rims and are surrounded by diffusion haloes. The chemical zonation of the garnets (Table 1) suggests growth from a "primitive", Mn-rich but Mg-, Fe-poor core composition. However, X_{Mg} is constant from core to rim. There is a weak increase in Ca from core to rim. A similar zonation was recorded from the synkinematic garnet in the basal Offerdal Nappe in the Tømmerås area (4: Table 8) and was tentatively interpreted as the result of an isothermal increase in pressure during the growth of the garnet. However, additional data are required to fully understand the implication of this particular zonation.

TABLE 1. Chemical composition of garnets, which syn- to post-date the phyllonitic foliation at the base of the Offerdal Nappe, Alsen Klippe, Jämtland. Analysts: Z. Solyom and T. Widmark. EDS equipment of the Inst. of Geology, Lund. Spec. No. IGCP CO-A-Alsen-19.

	Crystal 1		Crystal 2	
	core	rim	core	rim
SiO_2	37.51	37.89	37.48	37.52
Al_2O_3	21.22	21.47	21.30	20.76
FeO	22.03	27.47	21.56	27.77
MnO	10.18	3.30	10.75	3.00
CaO	8.47	9.62	7.72	9.81
MgO	0.49	0.70	0.58	0.83
Total	99.91	100.45	99.40	99.48
X_{Mg}	0.04	0.04	0.05	0.05

The Core of the Scandes

The low temperatures and incomplete equilibration of metamorphism at the deep tectonic levels of the central Scandes are at variance with models describing the basement of the Tømmerås Window as "basal gneiss", i.e. a part of the Western Gneiss Region, which has been considered to be the core zone of the Scandes (Ramberg 1966, 1967, 1980: p. 261 and Fig. 2, 1981: p. 130). The core zone concept developed largely from Ramberg´s experimental and theoretical models which had great impact on Caledonian research during the 1960s and early 1970s. In his buoyant rise models, basement penetrates cover as rising diapirs and cover becomes deeply infolded into basement. Ramberg has frequently compared the situation in the Western Gneiss Region to the gneiss culminations of the Bronzon Hill Anticlinorium in the northern Appalachians. However, Ramberg (1980: p. 264) has also pointed out that "it is not necessary that the basement should be especially ductile in order for segments of it to rise into the cover". He concludes that Precambrian structures and metamorphism may be preserved in rising basement "blocks". In this case, it appears less appropriate to refer to the basement uplifts in western Norway as the core zone of the *Caledonide* orogen, if "core zone" connotes maximum metamorphism and structural complexity.

On the whole, one may ask: Which part of a plate-collisional orogen is to be regarded as the "core"? If subduction zone conditions are emphasized, the Western Gneiss Region is a strong candidate (Griffin et al. 1982). However, the age of the high-grade (granulite facies) regional metamorphism in this region remains controversial. There is, moreover, a time factor involved: as will be shown in the next chapter, there is a critical lag behind of the temperature peak during metamorphism in extensive overthrust terrains. Therefore, with regard to the inferred "very rapid" uplift of the Western Gneiss Region after subduction (Griffin & Mørk 1981), temperatures did not necessarily reach high values during the ensuing decompression of the region. As far as synorogenic magmatic activity, migmatization and anatexis is concerned, the "core" of the Scandes is allochthonous. If, finally, late- to post-orogenic magmatism and anatexis is considered, the "core" of the northern Caledonide orogen is situated in eastern Greenland. On the basis of his study of the Precambrian basement of the Lofoten Islands Bartley (1982) concluded that only the upper 15 - 20 km of the continental crust was "Caledonized". Below that depth, basement behaved rigidly during the Caledonian orogeny. He compared the basement tectonics of this interior window with the décollement tectonics of the orogenic front. Clearly, in the Lofoten case the "core" of the orogen must be located far to the west of the Norwegian coastline, if intensity of basement diastrophism is held as the chief criterion. However, the margins of colliding plates were not necessarily "smooth" and the absence of severe Caledonian deformation in the Lofoten basement does not exclude the possibility of intense basement deformation in southwestern Norway.

The Tømmerås Antiform is a gentle fold cored by well preserved basement. In contrast, the Kolåsfjell-Flåtjern antiform-synform pair flanking in the west (Fig. 3) represents tight isoclinal folding of the basement-cover sequence. I suggested that post-Caledonian high-angle faulting could account for the structural and metamorphic contrast between the Tømmerås area and the adjacent Fosen Peninsula (Fig. 1; Andreasson 1978). The west-coast of Norway is dissected by a very prominent ENE-WSW lineament system, which was active during deposition of Caledonian molasse (Bryhni 1978) and perhaps even earlier (Rutland 1959; Gabrielsen et al. 1981; 8). Regional geological interpretations must take into account the latest major structures. Differential uplift along these faults could also explain the narrow, ENE-WSW trending troughs containing cover of comparatively low metamorphic grade, which occur as far west as the coast of northern Trøndelag. As will be discussed in the next chapter, erosion rates effectively control geotherms and therefore also the cooling and post-orogenic magmatic activity in nappe terrains. Differential uplift along deep fractures controls erosion rates and therefore indirectly the distribution of high-grade metamorphism. Returning to Ramberg´s models, the deep faults could represent boundaries of "rigid blocks" (Ramberg 1980: p. 264). Interestingly, the same lineament system defines the southeastern boundary of the Lofoten "block".

The Trollheimen Antiform (200 km southwest of Tømmerås) is of the same tectonostratigraphic build-up as the Tømmerås Antiform (Gee 1980) but late Caledonian (i.e. post-thrusting) folding was much more intense. Krill (1980, 1981) suggested that the structural aspects of Wegmann´s (1959) *Stockwerk* model could account for the tectonics of the Oppdal area. This model allows intense folding and metamorphism in the infrastructure while low-grade metamorphism and less ductile folding prevail in the superstructure (i.e. in this case the Støren Nappe). The model is attractive because it could explain how the outliers of Ordovician volcanics, for instance on the island of Smøla (Fig. 1), escaped deep downfolding into the "core". However, the sharp vertical metamorphic contrast between the lowest greenschist facies volcanics on Smøla and the basal gneiss can also be explained by the intense vertical shortening during Silurian nappe displacement (8). A vertical shortening of at least 15 km is clearly a factor to take into consideration when basement-cover relationships in the west are being modelled (Gee 1982). The Stockwerk model hardly explains the stro *lateral* contrasts in basement ductility and metamorphism between Tømmerås and Fosen I maintain that the extensive late Caledonian high-angle faulting can account for these contrasts. The Stockwerk tectonic process and the faulting ought to have been diachronous and do not exclude each other.

Much additional work, in particular mapping, is required before the orogenic implications of ductile and brittle deformation in Vestranden is understood.

Transient blueschist facies conditions in the deepest levels of the central Scandes?

The recorded low temperatures and incomplete equilibration in the deepest units of the Tømmerås tectonostratigraphy may seem at first sight to be at variance with the metamorphic conditions one would expect to encounter at such great tectonic depths. However, the results are consistent with the principles of recent models which describe the evolution of geotherms during extensive nappe displacement. In 1974, Oxburgh and Turcotte published a theoretical model for the perturbation of regional conductive geotherms during overthrusting and the subsequent relaxation of "saw-tooth" thermal profiles. Their model gave impetus to a series of studies which refined the initial model by taking into consideration other critical parameters, the most important of which is erosion (Bickle et al. 1975; Graham & England 1975; England 1977; England & Richardsson 1977; Draper & Bone 1980; Thompson 1981; Thompson et al. 1981). In the Scandes, the available age brackets and P-T estimates of Silurian nappe displacement do as yet not allow an application of quantitative models. The purpose of the following discussion is therefore to call attention to their potential relevance in the interpretation of the metamorphic evolution of the central Scandes, at least as far west as Tømmerås. The simple basic principle of the model (i.e. the slowness of post-thrusting temperature adjustment, which is due to the poor thermal conductivities of rocks) invites application also in small-scale contexts, such as interpretations of the order of porphyroblastic growth of minerals (6: p. 228).

Fig. 6 shows the increase with time of temperatures prevailing at the base of a nappe complex after its emplacement onto a continental basement with a surface temperature of 0°C. Oxburgh and Turcotte and other early students applied their models to the Tauern Window (Eastern Alps) which has the same principal tectonic build-up as the Tømmerås Window, i.e. a nappe complex overlying autochthonous--parautochthonous basement with a locally preserved sedimentary cover. Peak metamorphic temperatures at the top of the Tauern basement have been estimated to 550°C. Molasse deposition, which signalled "the erosional termination of metamorphism" started 20-25 Ma after thrusting (Oxburgh and Turcotte 1974; 30-35 Ma according to Bickle et al. 1975). Immediately after thrusting, temperatures at the interface between nappe complex and basement rose to one half of the initial temperatures prevailing at a depth corresponding to the base of the thrust complex (Oxburgh & Turcotte 1974: p. 646). The inversion caused by a hotter nappe emplaced above sediments of surface temperature disappeared within a few million years (c. 5 Ma). However, in order to get an idea of the slowness of the temperature adjustment, let us assume that the nappe complex emplaced above the Jämtland Supergroup of the Tømmerås Window was at least 25 km thick, as estimated from the minimum pressure of 0.7 GPa in the Gula Nappe during thrusting (p. 18). With an original "normal" gradient of 30°C/km

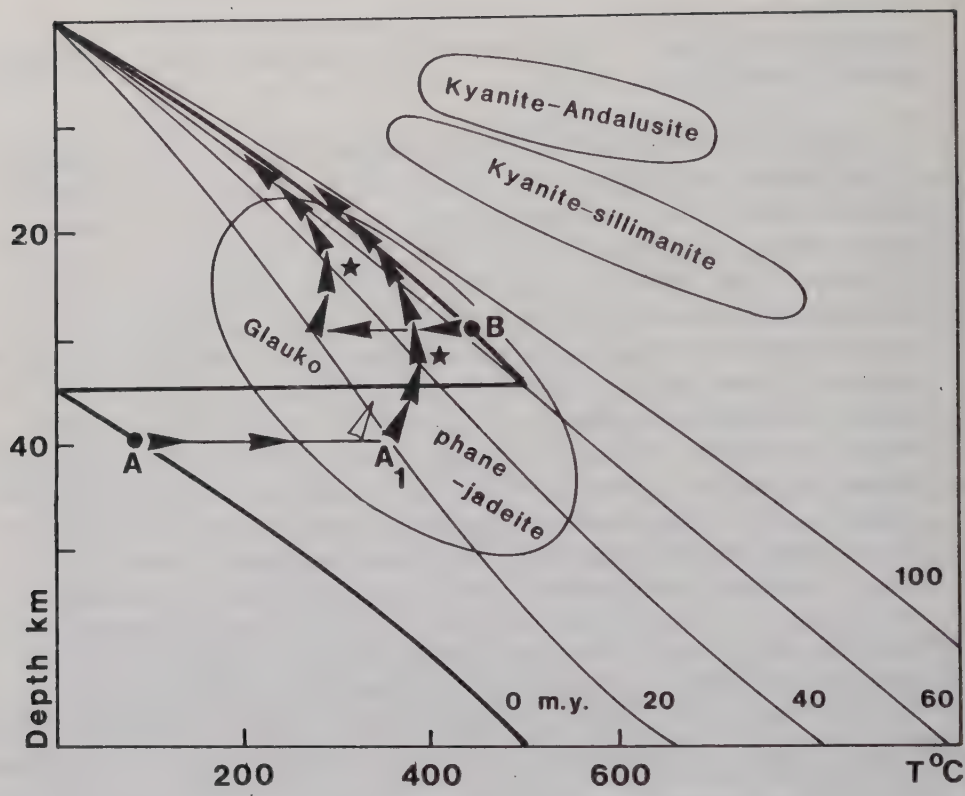


FIG. 6. Depth-temperature diagram describing the evolution of the conductive geotherm in overthrust terrains (compiled from Thompson 1981). The thick line shows the "saw-tooth" geotherm immediately after the emplacement of a 35 km thick thrust complex over rocks of surface temperature (i.e. c. 0°C). Thin lines represent the recovering geotherms 20, 40, 60, and 100 Ma after the emplacement. With erosion, a particular sample point (A_1) below the thrust will move upwards and to the right in the diagram (towards higher T); the resultant will be the P-T-t path shown by the arrows. A sample (B) close to the base of the thrust complex cools to about one half of the original temperature. The P-T-t paths of this diagram were calculated on the assumption that the rocks were permitted to heat at depth for 20 Ma before onset of erosion. The empty arrow shows where the P-T-t path turns upwards if erosion starts 10 Ma after overthrusting.

During the entire uplift to a depth of c. 20 km, the P-T-t paths stay within the stability field of galucophane-jadeite. Note that the temperature maxima ★ occur tens of millions of years after the onset of uplift and erosion.

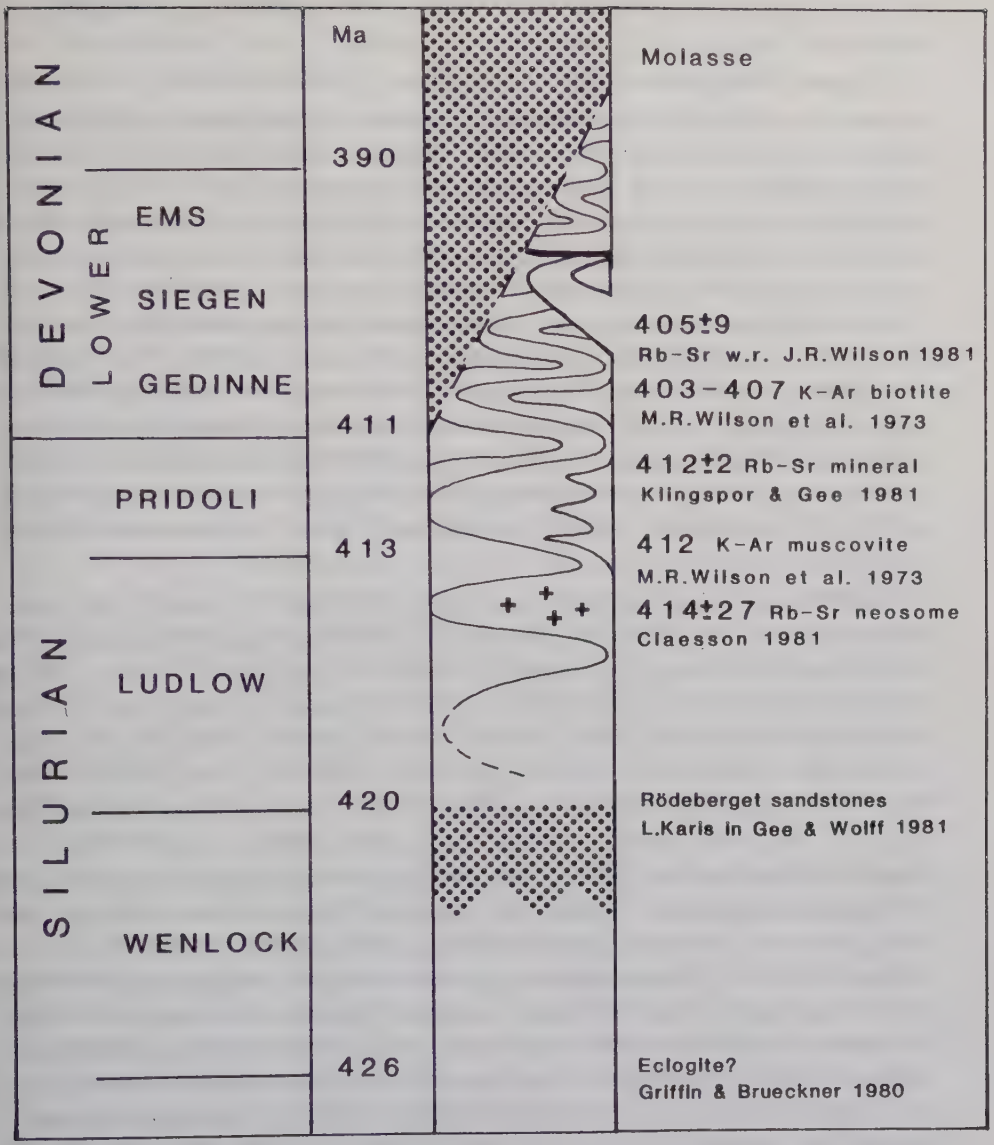


FIG. 7. Tentative time-table for the Late Silurian - Early Devonian in the Jämtland - Trøndelag districts. The table was compiled in order to estimate the time span between the end of thrusting and the onset of uplift and erosion. Thrusting occured after deposition of the Rödeberget sandstones (Fig.1:Alsen), which are the youngest Palaeozoic sediments in Jämtland and are no younger than Middle-Silurian in age (L. Karis). Radiometric age brackets in the second column were taken from McKerrow et al. 1980. Ages in the column to the right represent metamorphic events in the Seve Nappe (414Ma). and the Trondheim Nappe Complex, which occurred prior to thrusting. Major folding, regional metamorphism and thrusting postdate the 405 Ma differentiate (Fongen-Hyllingen)

it takes 60 Ma for the temperature in the overridden sediments to attain 550°C (Oxburgh & Turcotte 1974: Fig. 3).

Englands (1977) refined model, which allows the overthrusted unit to be heated at depth for 30 Ma before erosion, fails to account for the rapidly uplifted and cooled Sesia-Llanzo zone, which preserves high-pressure metamorphism. Rapid uplift implies rapid erosion, and the prospects of finding blueschists in an orogen of Caledonian age are therefore poor (England & Richardson 1977). Draper and Bone (1981) simulated the thermal history of a 30 km thick accretionary prism resting above oceanic lithosphere in a subduction zone. Upon cessation of subduction, the prism was subjected to a temperature rise due to thermal relaxation and radioactive self-heating. If no erosion occurred, the geotherm left the blueschist field after 26 Ma (at a depth of 30 km). After that, shallower rocks underwent prograde metamorphism within the amphibolite and the greenschist facies, whereas deeper rocks were metamorphosed within the eclogite facies. Even assuming that the prism had a rate of radioactive self-heating corresponding to that of greywackes, Draper and Bone conclude that an erosion rate of 0.14 cm $year^{-1}$ would be sufficient to preserve blueschist.

Application to the Tømmerås Window requires adjustment of several input parameters. However, the wholly dominant factor in the Tømmerås case is the rate of unloading and uplift. Fig. 7 is an attempt to use available, partly contradictory geochronological data to estimate the length of time between the cessation of extensive overthrusting and the beginning of molasse deposition in the central Scandes. Employing the time scale of McKerrow et al. (1980), there was a time span of at the most 20 Ma between thrusting over the Alsen sandstone in Jämtland and molasse deposition in the Røragen area (c. 50 km south of Sylarna, Fig. 1). Other radiometric ages provide much narrower constraints. The ages clustering around 415 Ma represent "transported metamorphism" (Andreasson 1980), the energy source of which must have been located far to the west of the Norwegian coast. Even less time for uplift is allowed by the $405^{+}_{-}9$ Ma age obtained by Wilson (1981) for the latest differentiates of the synorogenic Fongen-Hyllingen intrusions. Regional foliations and thrusting foliation cut these differentiates. Deposition of a Lower Devonian intramontane molasse on basement gneisses implies the erosion of a more than 25 km thick (cf. p. 25) nappe complex during less than approxiamately 10 Ma. This requires erosion rates of at least 0.25 cm $year^{-1}$, i.e. nearly twice the rate required for the preservation of blueschists (cf. above).

Thompson (1981; Thompson et al. 1981) combined the model of Oxburgh and Turcotte (1974) with the erosion-control model of England and Richardson (1977). So called P-T-time paths (the arrows in Fig. 6) describe the upward erosion-controlled movement of sample points on the successively restored geotherms. The important implication of Thompson´s model is, that P-T-t paths for a crust thickened by overthrusting are within the blueschist field during the entire uplift period (i.e. as long as the rocks are below a depth of 20 km). In the calculation illustrated in

Fig. 6, the rocks are permitted to heat at depth for 20 Ma before erosion sets in. As indicated above, such a long duration of heating is very unlikely in the Tømmerås case, which implies that the P-T-t path in Fig. 6 must be shifted to the left.

Erosion working from above and thermal relaxation acting from below combine to bring hot rocks and geotherms to higher levels of the nappe complex. Slow rates or long duration of erosion permit thermal relaxation to extend far upwards. England & Richardsson (1977) point out that maximum temperatures are attained at successively greater depths. In consequence, melts produced at depth during maximum temperatures will rise and penetrate rocks which have already passed their temperature maxima. Anatectic intrusions must therefore postdate peak regional metamorphism. In my opinion, this conclusion has an important bearing on the late- to postorogenic magmatic activity in the Western Gneiss Region. Small late- to postorogenic granite and pegmatite dykes (Krill & Griffin 1891; cf. also p. 23) have not necessarily been derived from "local anatexis not far from the site of emplacement". They may represent offshots from rising granite melts which have been generated at much greater depths, and may inform very little about the regional metamorphic history of the the rocks in the present-day erosion surface. As long as the age of regional anatectic rocks such as those in the northwestern Fosen Peninsula is not unambiguously assessed and shown to be identical with that of the dykes, small dykes and cooling ages do not prove "intense" Caledonian orogenesis in their occurrence areas. Thompson et al. (1981) found the overthrusting model (Fig. 6) inadequate to account for the large heat input required to establish kyanite-sillimanite conditions in the thickened crust, in cases where the geotherm was not initially high . In their opinion, massive underplating by mantle magma is required to achieve regional penetration of heat in a thickened crust.

The Alpine models assume single-phase overthrusting. In the Scandes, overthrusting occurred during the construction and collapse of the Scandian nappe pile. We do not know, whether this evolution was continuous or episodic (cf. p. 11). In addition, there was an early Caledonian event of ophiolite obduction, which must have caused drastic disturbance of the previous geotherms. We do not know whether and to what extent normal geotherms were restored before the Scandian overthrusting. Therefore, it appears possible that the metamorphic evolution of the Scandes was controlled by several generations of geotherms, which may, of course, greatly complicate the application of P-T-t models. Nevertheless, it is obvious that such models deserve attention. They introduce an important, previously disregarded time constraint on the energy budget of metamorphism in the Scandes (7: p. 353).

Volcanism in the early Iapetus Ocean and the derivation of the Särv and lower Seve Nappes

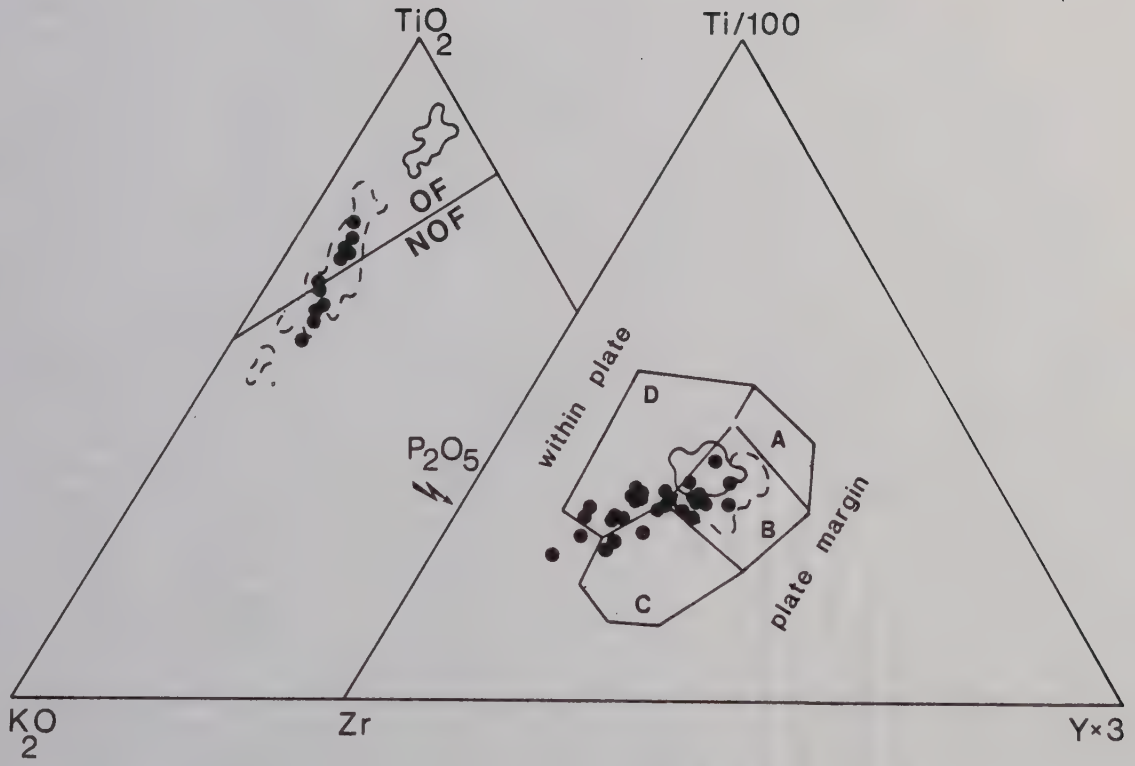
Petrochemical work (3) produced evidence supporting the extension of the Särv Nappes into northwestern Trøndelag (p. 8) and data relevant in the elucidation of the early orogenic processes (3,5). The conspiciuously transitional character of the Särv tholeiites as regards oceanic versus continental palaeotectonic settings (Solyom et al. 1979) is similar to that of the Trøndelag dolerites (3). In combination with the existence of an alkali-basaltic subgroup of Särv dolerites, this transitional magma character has been taken to indicate that Särv volcanism was related to continental rifting during the opening of the Iapetus Ocean (Solyom et al. 1979; 5). Such an interpretation also resolves for the seeming conflict between the oceanic environment implied by the chemistry of the dykes and the alluvial character of their country rocks (Kumpulainen 1980). A similar magma-tectonic development has been suggested for the Caledonides of Greenland (Pearce et al. 1975), the Scottish Highlands (Graham 1975), southwestern Ireland (Yardley & Senior 1982), the Proto-Tethys (Raza 1981) and the Red Sea (Gass 1970).

Massive epidote-amphibolite facies amphibolites occur in the lowermost Seve Nappes. Having a wide distribution and locally (Sylarna, Sarek, Kebnekaise) great thicknesses, these amphibolites document a very extensive magmatic activity. In the eastern parts of the 800 km long Seve belt in Sweden, these amphibolites occur in close spatial association with the dolerites of the underlying Särv Nappes. This conspiciuous field relationship suggests the possibilty of a primary magma-tectonic affiliation of the basal Seve and the Särv metadolerites (Strömberg 1969; Gee 1975a: p. 30; Sjöstrand 1978). In contrast, the considered basal Seve amphibolites, e.g. in the Helags - Sylarna districts (Fig. 1) , the lower Kall Nappe of Yngström (1969) the Eastern Seve belt of Williams and Zwart (1977) and the "eastern amphibolite" terrains of Norrbotten (Kulling (1982) differ from those of the high-grade Seve as regards the complexity of tectonometamorphism. This may indicate a difference of age so far, however, not controlled by radiometric datings. In the lower Seve, Koark et al. (1980) obtained Precambrian fission track ages on sphenes from the Fröå-Bjelke Nappe, which is, however, different from the lower Kall Nappe as regards metamorphis and deformation history (Andreasson & Johansson 1982: Stop 1-10).

Analyses of low-grade amphibolites from Mt. Sylarna (Helags Nappe, Fig. 1) show abyssal tholeiitic characteristics similar to those of the Särv dolerites (5). In addition, they indicate spilitization, which is compatible with a derivation from the floor of the early Iapetus Ocean. To identify the palaeotectonic settings, we employed discriminant diagrams based on "immobile" elements (P, Ti, Zr, Y, Nb). The Ti-Y-Zr diagram (Pearce & Cann 1973) has been extensively used for nearly ten years. However, its limitations when applied to metamorphic rocks have often been disregar-

ded, and misinterpretations of tectonic settings have been the result. On the whole, the application of these popular diagrams suffers from still insufficient knowledge of the factors controlling the siting of the incompatible elements during melt crystallization and their possible redistribution during subsequent ocean-floor metamorphism or weathering. Nevertheless, mismatch between indicated magma environments and observed geological settings must not necessarily indicate a malfunction of the method, which has been shown for the Särv dolerites. However, it is evident that Pearce and Cann diagram may fail to account for crustal or mantle anomalies below the site of magmatic activity. Problems concerning the secondary redistribution of "immobile" elements are clearly critical in our interpretation of the petrochemistry of the Sylarna amphibolites. There seems to be little reason to assume that the specific pattern defined by Na_2O, CaO, Al_2O_3, K_2O and the oxidation ratio had resulted from regional metamorphism or wall-rock interaction. These amphibolites are thick and massive. The sampled suite is chemically homogeneous, which is evident from the low standard deviations (3: Table 1). Penetrative recrystallization during low-grade metamorphism can possibly explain such homogeneity on the scale of a hand specimen, but hardly on the scale of a massif of the size of Mt. Sylarna. We concluded that the chemical compositions have not changed after spilitization. A redistribution of elements may, on the other hand, have occurred during spilitization. Hart et al. (1974 and further references in their Table 3) show that K increases during sea floor alteration of basalts, whereas Bischoff and Dickson (1975) demonstrate that such change occurs only at temperatures below 200°C; above this temperature, K is leached. However, the K (and Rb) concentrations of the Sylarna amphibolites (Fig. 8) are too low to be the result of leaching only, and are considered valid indicators of an oceanic affinity. Concerning the incompatible elements, most studies suggest that the effect of sea floor alteration is weak (Thompson et al. 1973; Hart et al. 1974; Loeschke 1975; Winchester & Floyd 1976; Coish 1977; Stern & Elthon 1980 a.o.) and may be detected (Williams & Floyd 1981) from petrographical properties. On the basis of the chemical properties of the Sylarna amphibolites and regional tectonostratigraphic considerations we suggested that the Särv amphibolites had been associated with the rifting and early break-up stages of the Baltoscandian-Greenlandian continent, whereas the massive, spilitic amphibolites of the lowest Seve Nappe had been derived from the early floor of the Iapetus Ocean.

Hill (1980) analyzed "greenschists" from the base of the Seve Nappe at Ramundberget, about 40 km to the south of Mt. Sylarna. In that area, the Seve is conspicuously heterogeneous, carrying lenses of marble, epidotite, acid volcanics and sulphide mineralizations. Although the chemistry is less homogeneous than that of the Sylarna amphibolites, incompatible elements indicate a similar magma-tectonic environment. The presence of CO_2 can have caused greater mobility of the incompatible elements (Williams & Floyd 1981). Judging from the Na_2O, CaO and Al_2O_3 contents


TiO2
Ti/100
OF
NOF
P2O5
within plate
D
A
B
C
plate margin
K2O
Zr
Y×3

of the Ramundberget metabasites, spilitization was less intense.

A primary geotectonic affiliation of the Särv and Seve rocks must be considered also for other reasons (7: p. 343). The alleged lack of metamorphosed Särv rocks in the cover succession of the Scandes is hardly consistent with current models postulating a general westward increase of the intensity of tectonometamorphism of the Baltoscandian margin *with its Upper Proterozoic sedimentary cover*. This poses the question whether Särv units could actually have metamorphosed equivalents in the rock pile of the Seve. Pilot studies (Andreasson et al. in press) suggest that the eclogite- and metadolerite-bearing meta-arkosic rocks of the Seve belt in southern Norrbotten are in fact Särv units.

Alkaline-ultrabasic rocks are extremely rare in central Norway. A biotite lamprophyre dyke cuts Ordovician limestones of the Støren Nappe on the island of Ytterøy (Fig. 1; Carstens 1961). This dyke has been dated to the Middle to Upper Devonian (Storetvedt 1967; Priem 1968). At Vive, east of Steinkjer and about 35 km northeast of Ytterøy, I found five decimetre-thick dykes cutting metasediments of inferred Särv affinity. Later, I found another swarm of narrow (< 30 cm) dykes cutting Offerdal metasediments 3 km east of Vive (Bruem). These dykes compare well with certain alnöitic (beforsitic) rocks (3: p. 59-65). Normative compositions, element ratios and high contents of Nb and Zr accord with those of the ultra-potassic lavas of the East African Rift. However, due to differences between the Vive and Bruem dykes as regards palaeomagnetic properties and the effects of Caledonian tectonometamorphism, we tentatively suggested that the Bruem dykes were pre-Caledonian and the Vive dykes late- to post-Caledonian in age (3: p. 65-66). There is reason to revise this interpretation. The alkaline-ultrabasic dykes occur in three different nappes of widely different derivation and tectonic level (Offerdal, Särv and Støren Nappes). However, they are all within a very short (40 km) strip along the inner Trondheimsfjorden. Such dykes are easily overlooked and future systematic mapping will no doubt report a wider distribution. However, in regional contexts, we may regard the occurrences at Ytterøy, Vive and Bruem as three virtually coinciding "pin-pricks". The probability that three "pin-pricks" in three different nappes have come to rest above each other must be very small. I therefore prefer to regard all mentioned dykes as being post-thrusting in character and late- or post-Caledonian in age.

FIG. 8. (opposite page). Diagrams of Pearce et al. (1975; left) and Pearce & Cann (1973; right) to show the magma character of the Särv dolerites in the Tømmerås area (dots), the Sylarna amphibolites (field drawn in full line) and the Särv dolerites in Jämtland (field drawn in dashed line; Solyom et al. 1979). OF = oceanic field. NOF = non-oceanic field. A = low-K tholeiites of island arcs. B = ocean floor basalts. C = calc-alkali basalts of volcanic arcs. D = within-plate basalts. Note the transitional character of the Särv dolerites. From (3: Fig. 10) and (5: Fig. 8).

Suggestions for future research in the Scandes

Reconstructions of fragmented orogenic belts must be based on interdisciplinary and intercommunicative work. Tectonic models must comply with such global patterns as those of e.g. faunal provincialism and with results obtained in far-off segments of the orogen. The rapid progress of Caledonide research in Scandinavia during the last ten years is essentially the result of interdisciplinary work organized by the national working groups of major international projects (p.1). From the particular aspects of Caledonide geology dealt with in this review it is obvious that future studies of the polyphase tectonometamorphic evolution of the central Scandes will require close cooperation of petrologists, structural geologists, stratigraphers, isotope geologists and geophysicists. Geochronological data indicate not only the ages of the rocks but also the rates of deformational and metamorphic processes. A future detailed time-table of Silurian nappe displacement will both serve the immediate needs of Caledonide research and provide the basis for an advanced study of the energy budget of metamorphic processes during large-scale crustal movements as well as during small-scale, strain-related recrystallizations of nappe margins. Better age brackets for the aggregation and collapse of the nappe pile will also allow an increasingly quantitative modelling of the remarkable mega-lens structures. The extensive occurrence of low-grade, massive Seve amphibolites associated with eclogites and quartz-feldspathic, locally calcareous sediments documents a very important igneous event and ensuing high-pressure metamorphism. It goes without saying that such an evolution, if Caledonian in age, must be a cornerstone in all orogenic reconstructions. A combined petrochemical, metamorphic, radiometric and sedimentological effort is required here. These examples clearly illustrate the benefits of continued international and interdisciplinary approaches to future research in the Scandes.

In Sweden, there is a traditional tendency to discriminate between "highland" (i.e. Caledonide) geology and "Precambrian" geology, when planning and conducting research. This attitude has prevented the recognition of the Scandinavian Highlands as a unique terrain for advanced studies in most major geological branches including even Precambrian geology. Several fundamental subjects of petrology are best studied in nappe terrains (Thompson 1981; 4). The nappe terrains of the Swedish Highlands provide excellent opportunities to conduct fundamental research on deformational processes. Regrettably, these opportunities have not been taken often enough. The state of preservation of volcano-sedimentary associations allows advanced studies of these subjects in their orogenic context.

The Caledonides are a gate-way to the Precambrian, a link between modern and Proterozoic geodynamic processes. They provide our most ancient opportunity to conduct a coherent study of a plate-tectonic orogenic evolution. In Precambrian

terrains, the evidence is fragmental and usually controversial. In the Scandes, we are still able to climb the trinity of an ophiolite complex and to sample glaucophane, even though that mineral occurs as inclusions in eclogite garnets (Krogh 1980). We can estimate the scales and rates of plate processes and the physical conditions of the Late Precambrian crust. The westernmost extension of the Fennoscandian Precambrian was welded to new crust by the Scandian tectonometamorphic event. The deeply eroded Scandes provide a rare opportunity to follow such a process in detail and to draw inferences which are cardinal in the study and interpretation of Precambrian fold belts.

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I am indebted to my co-authors for giving me free hands to summarize and comment upon joint results. I alone am responsible for any over-exploited or degenerated ideas.

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My work in the highlands has benefited from discussions with many colleagues. However, many of the productive ideas and initiatives of highland research during the last decade have emanated from one and the same person: David G. Gee. Not least my work has profited greatly from his creativity.

References

GFF = Geologiska Föreningens i Stockholm Förhandlingar
NGT = Norsk Geologisk Tidsskrift
NGU = Norges Geologiske Undersøkelse
SGU = Sveriges Geologiska Undersökning

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